

TECHNO-ECONOMIC ASSESSMENTS BY THE ZERO EMISSION COAL ALLIANCE

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TECHNO-ECONOMIC ASSESSMENT OF THE ZERO EMISSION COAL ALLIANCE TECHNOLOGY

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ABSTRACT

This paper reports on a preliminary technical and economic assessment of a novel, anaerobic technology for generating electricity and/or hydrogen from coal at very high efficiencies and with zero releases of carbon dioxide and airborne contaminants to the atmosphere. The study, sponsored by the Zero Emission Coal Alliance, an alliance of coal, mineral production and power industries as well as governments and research organizations, assessed the viability of a zero emission coal concept originated at the Los Alamos National Laboratory. The technology includes hydrogasification of the carbon feed, production of hydrogen, and carbonation of the produced CO₂ with lime. The hydrogen is used in high-temperature fuel cells to produce electric power and the calcium carbonate is calcined to produce a pure stream of CO₂ for sequestration by means of a mineral carbonation process. The assessment did not identify any fatal flaws and concluded that the technology shows good potential performance with high busbar efficiency (around 70%) and competitive costs when compared with other advanced power generation technologies. Actions to accelerate the development of the technology and build a zero emission pilot plant within 5 years are discussed.

INTRODUCTION

In late 1999, an alliance comprised of private industry and government agencies was formed based on the recognition that carbon dioxide emissions from coal are a major contributor to the world's overall greenhouse gas emissions and that far-reaching actions are required if coal and other carbon-based fuels are to continue as viable energy sources in our national economies. This alliance, the Zero Emission Coal Alliance (ZECA), included 18 members, about evenly divided between Canadian and United States members, with one European participant. The private sector members represented the coal and minerals production and power generation industries, whereas the government agencies included the Los Alamos National Laboratory (LANL), the Canadian federal government and the Alberta provincial government. Technical advisors to the Alliance included the U.S. Department of Energy, the Electric Power Research Institute and the National Mining Association. A list of all ZECA members is given in Table 1.

The objective of ZECA was to pursue a novel technology concept, originated at the Los Alamos National Laboratory (New Mexico, USA), for the generation of electricity and/or hydrogen from coal with zero atmospheric emissions and high efficiency^{1,2}, while producing a stream of high-purity CO₂ which would be sequestered as a mineral carbonate.

In May 2000, ZECA contracted Nexant, Inc. (a Bechtel company) to prepare technical and business plans for the Alliance. The major objectives of ZECA for this phase of work were to determine the technical and economic feasibility of the zero emission coal (ZEC) concept (the Technical Plan) and to create a plan for the pathway to build a pilot plant (the Business

Plan) in about five years. These Technical and Business Plans were completed in April 2001, and this paper is drawn from these reports as well as related conference presentations.^{3,4} In a follow-up study, Nexant visited a large number of process developers and equipment/materials suppliers in the U.S. and Canada, discussed with them the ZEC process, collected pertinent information and explored their potential participation in future ZEC developments.

With the assessment studies successfully completed, ZECA had fulfilled its mandate and was disbanded. While at this stage of the investigation a number of uncertainties remained about the concept's technical and economic features, no fatal flaws were identified and the concept was shown to be competitive with other advanced power generation technologies. This was the basis for the decision by most ZECA participants to further pursue the development of the ZEC technology. A new, for-profit organization, ZECA Corporation, was formed in November 2001 to replace the former Alliance. Its near-term objectives are to design and construct a pilot plant that will operate in about five years, with the first two to three years needed for process R&D, component selection and design of the pilot plant.

BRIEF DESCRIPTION OF THE ZEC CONCEPT

The overall concept of the ZEC technology is shown in Figure 1. The concept consists of two separate main components: a hydrogasification and power production plant, and a mineral carbonation plant for CO₂ sequestration.

The hydrogasification process converts coal or other carbon feedstocks to a synthesis gas of mainly methane and hydrogen. This synthesis gas is reformed with steam at pressure and temperature to produce a relatively pure hydrogen stream through the use of a CaO carbonation reaction. The carbonation reaction removes the CO₂ and supplies the energy needed to drive the reforming reaction. Electric power is produced from the product hydrogen in a solid oxide fuel cell (SOFC), which is especially designed for the coal-based plant. A calcination reaction, driven by process heat from the solid oxide fuel cell, recycles the CaO and produces a stream of CO₂. This stream of CO₂ is compressed at the power plant and sent to the nearby mineral carbonation plant or, alternatively, to a pipeline for use or disposal elsewhere.

At the mineral carbonation plant, the CO₂ is reacted at pressure and temperature with magnesium silicate (serpentine or olivine) produced at a nearby serpentine mine. The resulting magnesium carbonate and silica end products are then returned to the mine for disposal. The magnesium carbonate is benign and thermodynamically stable, thereby guaranteeing permanent sequestration of the CO₂.

The anaerobic hydrogen production process is an elevated-temperature process, which requires no air (hence the term anaerobic), involves no combustion and requires no heat input. Aside from the coal, the process requires only water and lime as inputs, with the latter two being continuously recycled. A high coal-to-electricity conversion efficiency, on the order of 70%, should be achievable. This high efficiency greatly reduces the CO₂ disposal costs per unit of electricity produced.

Another key environmental advantage is that, apart from CO₂ emissions, the process also eliminates all other emissions to air. The ash from the coal is fully contained, making compliance with restrictions on particulate emissions straightforward. Sulfur in the coal is removed in solid form (calcium sulfate), eliminating hydrogen sulfide or SO₂ emissions. Also, due to the absence of combustion and thanks to the reducing conditions in the vessels, there is no formation of NO_x. Instead, nitrogen will be removed as ammonia. The closed-loop

nature of the process greatly simplifies the removal of any remaining contaminants introduced by the coal, such as mercury, PM2.5 and heavy metals.

GASIFICATION AND POWER GENERATION

The gasification and power production processes are illustrated in Figures 2 and described in more detail in the following paragraphs. Process temperature and pressure conditions are key to process performance and economics, thus process integration was and remains crucial for the technical and economic feasibility of the ZEC process.

Hydrogasification

Hydrogasification was chosen as the gasification technology as the reaction of coal with hydrogen is exothermic, thereby eliminating the need for heat input to this part of the ZEC process. The original concept from LANL did not specify a particular hydrogasification technology, so one of the first issues for the technical assessment was to find a suitable gasification technology – one that fits the overall scheme and one where sufficient experience with downstream operations and overall energy and material balances exists. Based on these considerations, the hydrogasification process developed by the Institute of Gas Technology (IGT) was selected.

Coal or other carbon fuel is fed to the gasifier as a solid or slurry, depending on the fuel properties, together with a recycle stream of hydrogen and steam generated in reformer #1. The major reactions in the hydrogasifier are:



The product gas of the hydrogasifier is composed mostly of methane, unreacted and recycled hydrogen and water from reformer #1, some CO and CO₂, and smaller amounts of other coal constituents. Pressure and temperature conditions in the gasifier are 1,500° F and 885 psia.

Ash from the gasifier is removed at the gasifier bottom and the hydrogasifier product gas is sent to the desulfurization unit prior to further processing. Hot gas desulfurization using lime is one of the areas now being investigated. The limits on sulfur content in the product hydrogen will depend on the sulfur tolerance of downstream elements. Particulates will also be removed in the gas cleaning step. Details have not yet been defined, but commercial cyclones and high temperature filters are expected to be employed.

Reformer-Carbonator

The desulfurized gas is sent to a reformer/carbonator unit where two reactions are completed:



Because the gasifier converts the largest amount of coal to methane at high temperatures and pressures and because the reforming step prefers lower pressures to convert the methane to hydrogen, two carbonator-reformer units are envisioned. The first unit operates at a high gasification pressure and provides the recycle stream needed for hydrogasification. The second unit operates at lower pressure to complete the reforming operation and produces the product fuel gas for the solid oxide fuel cell.

In reformer #1, steam reacts with the methane to produce hydrogen and CO₂ (reaction 1). The CO₂ then reacts with the lime (CaO) to produce calcium carbonate (CaCO₃) (reaction 2).

The reformer #1 effluent is divided into two streams. The recycle H₂ stream is compressed and fed to the gasifier. Because the gasifier and reformer #1 operate essentially at the same pressure, minimum power is required for the recycling of the hydrogen stream, which is a major part of the ZEC concept.

The remaining product gas from reformer #1 is sent to reformer #2, which also receives liquid water and steam. The temperature in reformer #2 determines the ratio between the liquid water and steam. The same reactions that take place in reformer #1 also take place in reformer #2. However, because reformer #2 operates at lower pressure and there is additional steam present, reaction conditions allow additional hydrogen production in this reformer. The product hydrogen from reformer #2 is fed to the SOFC. Reformer #2 and the SOFC are essentially at the same pressure, so again minimal power is required for compressing steam for reformer #2.

In summary, the major process conditions are:

| | | |
|-----------------------|----------|---------|
| Hydrogasifier | 885 psia | 1500° F |
| Reformer/Carbonator 1 | 885 psia | 1480° F |
| Reformer/Carbonator 2 | 435 psia | 1480° F |
| Solid Oxide Fuel Cell | 425 psia | 2100° F |

A reforming catalyst, preferably one with good sulfur tolerance, promotes the reforming reaction in the reformer/carbonator operations. Preliminary investigations with catalyst developers indicate that a year or more will be required to develop a suitable reforming catalyst.

Calciner

After reforming and CO₂ carbonation, the next process step is the calcining of the CaCO₃ formed in the reformer-carbonator back to lime by the addition of heat. The calciners are fixed bed reactors, where lime is heated indirectly by hot CO₂ that circulates between the SOFC heat exchanger and the calciner heat exchanger, and maintains the calciner temperature at 1,680° F. At this temperature, CaCO₃ is decomposed to CaO and CO₂, with a CO₂ pressure of about 19 psia, according to:



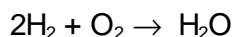
The product CO₂ is compressed to 1,000 psi and sent to the mineral carbonation plant or pipelined for use or disposal elsewhere. The concept of carbonation of lime with CO₂ is partly based on literature describing the Consol CO₂ Acceptor process piloted in the 1970s. Also, in the mid to late 1990's, Harrison et al. successfully tested the combination reaction of reforming and lime carbonation in one reactor, thus avoiding the need for heat exchangers.

The reforming – carbonation – calcining steps are at the core of the ZEC concept. The base case operation is envisioned as a semi-continuous process where reforming and carbonation are performed in one reactor, and then gas streams are changed so the same reactor can be used as the calciner. This semi-continuous operation avoids moving hot solids between the vessels. However, discussions with equipment suppliers indicate that re-examination of this issue will be worthwhile before designing the pilot plant.

Solid Oxide Fuel Cell Power Generation

The product fuel gas, primarily hydrogen, from reformer #2 is sent to a high-temperature SOFC, which produces electric power and the thermal energy needed for the calcination step. Since the gas arrives at about 1,500°F and the fuel cell must operate at 2,100°F, the gas is heated to 2,100°F with the heat from the SOFC exhaust. Similarly, the compressed

air for the SOFC, which enters at 950°F, is boosted to 2,100°F by exchanging heat with the SOFC exhaust stream. In the fuel cell, oxygen from the air permeates towards the fuel side of the SOFC and reacts with the hydrogen to form water:



Part of the energy of the reaction directly produces electricity and the remaining energy, which is in the form of heat, increases the temperature of the SOFC exhaust/effluent streams. The SOFC has two effluents: H_2O in the form of steam and oxygen-depleted air. The thermal energy from both SOFC effluents is exchanged to heat the SOFC feeds, to supply the calcination heat (using CO_2 as the heat carrier) and the steam for the reformers. Finally, portions of the steam and the oxygen-depleted air are sent to steam turbine and air expander units to produce additional electric power.

At present, SOFC development is focused on building distributed generation-size units and on lower operating temperatures in units for transportation uses, both of which will use natural gas as the main feedstock or possibly liquid fuels reformed to suit the SOFC. However, the ZEC concept requires a SOFC, which can accept hydrogen with traces of sulfur, mercury, ammonia and other chemicals from the feedstock. Such SOFCs for operation with synthesis gas from coal and other solid fossil feedstocks have not yet been designed, tested and manufactured. This need for a high-temperature, coal-compatible fuel cell is not limited to the ZEC technology. Indeed, a version of such a fuel cell will be needed for most new, high-efficiency, advanced coal-based power generation technologies. Ideally, such a coal-compatible fuel cell would be capable of operating at high temperatures (2000-2200°F would best suit the ZEC concept), have a built-in heat exchanger, be sulfur-tolerant and maintain a complete separation of the fuel/fuel exhaust side of the fuel cell from the air side of the fuel cell.

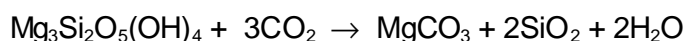
Contaminant Removal

The ZEC technology is effectively a closed-loop process. Except for the depleted air on the air exhaust side of the SOFC, there are no releases to the atmosphere. The ZEC concept includes the capture and removal of all contaminants introduced by the coal – a task that is greatly simplified by the closed nature of the process. The effectively closed-loop system allows internal contaminants to build up to a level where they can be easily handled. Operating a slipstream, one can apply relatively inexpensive contaminant processing, while still removing all of the contaminants originally contained in the coal as a solid or liquid. This is in contrast to present-day coal combustion systems, which vent directly into the atmosphere and where, therefore, removal efficiencies must be extremely high (and expensive) to reach typical low emission levels in the parts per million range.

While the work to date has focused on the removal of particulates, sulfur and CO_2 , future process design engineering and tests will investigate the collection and disposal of volatile trace contaminants (such as mercury), fine particulates ($\text{PM}_{2.5}$), and heavy metals.

MINERAL CARBONATION - CO_2 SEQUESTRATION

The CO_2 stream from the calciner units will be permanently sequestered by reacting it with abundant, naturally occurring minerals to form harmless, stable mineral solids, which will not leave a CO_2 legacy for future generations. In the carbonation process, CO_2 reacts with magnesium-rich silicates (serpentine or olivine), yielding magnesium carbonate, silica (quartz) and possibly water according to the reaction:



The end products are all naturally occurring and the reaction is actually part of the natural geological carbon cycle. The magnesium carbonate product is thermodynamically extremely stable and, hence, its disposal in depleted mines is truly permanent.

The mineral carbonation process is at an early stage of development in an ongoing U.S. Department of Energy program and is described in several papers.^{5,6,7} Laboratory work is performed at Los Alamos National Laboratory, the Albany Research Center, the National Energy Technology Laboratory and the University of Arizona.

The Nexant feasibility study, while focusing mainly on the gasification and power generating processes, conducted preliminary engineering assessments of performance, equipment and costs for the mineral carbonate process and, most importantly, indicated process changes that would increase the concept's opportunities to become a commercial sequestration process. A detailed discussion of the mineral carbonation process and the Nexant assessment of this process is outside the scope of this paper.

The large mining and mineral preparation operation needed to support the carbonation process was not viewed as a major technical constraint for the process. In one design case, some 38,000 tons per day of raw serpentine were required to treat 13,000 tons of CO₂ captured from a 1,000 MW_e ZEC power plant. These quantities of solid materials are comparable to other large-scale mining operations. From a political and social point of view, mine, plant and disposal siting issues will need to be examined in the larger context of climate change trade-offs which will be determined as CO₂ emissions are regulated.

The starting magnesium silicate minerals exist in vast, rich deposits in coastal regions around the world. Taken together, the world's rich magnesium silicate deposits are sufficient to easily handle the entire world's coal supply.

ZEC POWER GENERATION PERFORMANCE

The ZEC gasification and power production process has the potential to achieve a high efficiency. Performance was estimated using Aspen Plus™ to simulate the operation of a 200-MW_e net power production plant, including pressurization of the CO₂ stream to 1000 psi but not including sequestration. The results are shown in Table 2. [A 200-MW_e size was used for modeling based on the maximum possible size of a single hydrogasification reactor. Costs shown hereafter are factored to a more typical coal-fired plant size of 600 MW_e, or three trains of the 200 MW_e system.] Table 2 shows efficiencies of around 70% calculated for busbar electricity generated from a base-case Wyoming coal and two alternative feeds.

The explanation for these high efficiencies is as follows. The gaseous product of the reformer-carbonation vessel contains four moles of hydrogen per mole of carbon that is introduced into the gasification vessel. Half of this hydrogen stems from the hydrogen in the methane that is generated in the gasification vessel. This hydrogen is recycled to the gasification vessel to gasify more coal, thereby closing the coal gasification loop. The other two moles of hydrogen are derived from the water. It is this latter half of the hydrogen that is the true product. Because the hydrogen production reaction takes up the heat of the CaO→CaCO₃ carbonation reaction, the hydrogen product stream contains approximately 150% of the energy brought into the process by the carbon. Conceptually, all of this energy from the hydrogen is available for electricity generation. Thus, even if the electrical generation process is only 50% efficient - a typical number for SOFCs - one still converts 75% of the energy brought into the process by the carbon into electricity.

However, unless one has a free source of CaO, the energy loan from the carbonation reaction must be repaid. This is done in the calcination vessel, where the high-temperature

waste heat generated by the SOFC is utilized to calcine the CaCO_3 . Since the process utilizes the waste heat of the SOFC, it is highly efficient. Taking into account various losses and assuming a realistic conversion efficiency for the SOFC, a high conversion efficiency, on the order of 70%, for the conversion of coal energy to electrical energy should indeed be expected. This also implies that the ZEC process will generate about 50% less CO_2 , for the same amount of electrical energy delivered, compared to conventional processes. This, in turn, greatly reduces the CO_2 disposal cost per unit of electricity produced.

ZEC ECONOMICS

Cost Estimates

Cost estimates for a 600-MW_e net gasification and power production plant are shown in Table 3. Costs for installation, construction materials and other items constituting a total plant were estimated from informal quotes, published data, experience with similar plants and other design studies. Costs for the fuel cells assume a mature technology and a price determined in discussion with Siemens-Westinghouse. The SOFC estimate does not reflect design and manufacturing changes that will be needed to make the SOFC design capable of operating with coal synthesis gas. At present it is not known if the design changes will reduce or increase the estimated cost.

Table 3 clearly shows that the SOFC and associated equipment are the major cost component in the estimate. Neither the cost nor performance of the process has been optimized, and there appear to be areas for improvements, as well as areas where better definition and engineering can reduce uncertainties. The performance and costs depend on a number of components that require significant R&D to make them commercial. Development costs, R&D and the other costs required to bring this new technology to maturity are not included in the estimates.

Comparison of Power Generation Plant Economics

The economics of the gasification and power generation portion of the ZEC technology were compared with those of other advanced power generation technologies with CO_2 separation and capture using data from two recent publications. The ZEC technology was found to potentially compare favorably with these alternative technologies.

The first publication is based on an Electric Power Research Institute (EPRI) study of two natural gas-fired turbine combined cycle technologies (NGCC), an integrated gasification combined cycle technology (IGCC) and two advanced pulverized coal technologies.⁸ Table 4 summarizes the data from the paper. The second reference is a study performed at the Massachusetts Institute of technology (MIT) and also includes NGCC, IGCC and PC technologies.⁹ Data from this study are summarized in Table 5.

In Tables 4 and 5, CO_2 removal costs are calculated from the amounts of CO_2 removed and the differences between the cost of electricity between plants with and without CO_2 removal. These removal costs can be used to compare the various alternative technologies. However, the ZEC technology's gasification and electric power production does not have an alternative design where CO_2 is not removed, since CO_2 removal is an integral part of the concept. Thus, a comparison of the ZEC technology with other advanced technologies can only be made on the basis of cost of electricity with CO_2 removal.

Table 6 compares the ZEC technology with the advanced technologies reviewed in the EPRI and MIT papers. Fuel prices were not provided in either paper, but from discussions with EPRI it was learned that the cost was \$2.70 per million BTU for natural gas and \$1.24 for coal. Obviously, higher natural gas prices will have a strong negative impact on the NGCC

plants. Both references use a 90% CO₂ capture factor in their work. The ZECA case includes a significant annual cost for the reforming catalyst and the periodic replacement of SOFC equipment (a 5-year economic life is used for the fuel cell modules). Total plant costs and efficiencies used in the comparison are shown in the table. Availability was adjusted for all cases to 90% of capacity, and the financial terms were set at a 12% interest rate and a 20-year investment term. These factors were applied to the cost data in Tables 5 and 6.

Process and project contingencies, which are typically accounted for in the total plant cost, were not included. This was done as the differences in levels of technology development of the various technologies are large, and contingencies for the ZEC technology cannot be estimated on a basis equivalent to that for the other advanced systems, which have been studied in much more detail for several years.

Also not included in the economic comparisons were the potential benefits to the ZEC technology of the removal of all contaminants. If one were to impose PM2.5, mercury and other capture requirements on conventional or advanced power plants designs, their costs would be strongly impacted by increased equipment costs and reduced efficiencies.

Advanced high-efficiency power generation technologies, especially those based on coal with their relatively high capital costs, have had very difficult times entering the commercial market. The low cost of fuel makes efficiency a minor factor in economic evaluations. However, when climate change considerations are incorporated into the analysis, efficiency becomes a much stronger economic driver. In the most concise explanation: if one is going to pay significant amounts for the capture and sequestration of CO₂, there are clear economic incentives to limit CO₂ production at the power plant by the efficient use of the carbon-based fuel.

It is, therefore, informative to compare the cost of electricity for systems that combine power generation, CO₂ separation and pressurization with sequestration. In Figure 3, the estimated costs of electricity are shown for the ZEC technology and three other representative technologies (the NGCC-1, IGCC and USCPC cases from the EPRI study). The sequestration method is not specified, but the generic costs are assumed to be in the range from \$0 to \$30 per ton of CO₂. While the accuracy and comparability of numbers can be debated, the important new feature is how the cost lines for coal technologies diverge, with the slopes strongly impacted by efficiency and the amounts of CO₂ that needs to be sequestered. As Figure 3 indicates, under the fuel price scenarios stated above, the cost of electricity for the ZEC technology is comparable to that of natural gas combined cycle technologies across the range of sequestration costs.

NEXT STEPS AND FUTURE PLANS

With the recent formation of ZECA Corporation, activities in the areas of investment fund raising and increasing the international participation from governments and industry, particularly in Europe, are being stepped up. In addition, a number of more technology-directed initiatives are underway.

ZECA Corporation is sponsoring hydrogasification tests at the Gas Technology Institute (Chicago) to collect data on carbon conversion in the hydrogasifier and raw gas composition, both of which will affect the ZEC process conditions. More sophisticated, larger-scale hydrogasification tests are planned for later in 2002. These tests will be planned to provide data for the calculation of energy balances around the gasification reactions and expand data on the synthesis gas composition.

Natural Resources Canada (NRCan) was contracted to perform a preliminary assessment of issues related to the carbonation/calcining steps of the process and a report has just been prepared. Likewise, Kinectrics (Mississauga, Canada) has submitted a report with recommendations for development work on a coal-compatible fuel cell. ZECA Corp. will consider both reports for action in the near future.

Efficient carbon-based hydrogen production using ZEC technology would have a variety of applications in conventional petroleum refining, oil sands processing and, in the longer term, as an energy carrier to supplement and replace natural gas and traditional transportation fuels. ZECA Corporation will evaluate process designs for hydrogen production to determine optimum conditions and assess the feasibility of using the ZEC technology, or some variation thereof, to co-produce hydrogen with electric power.

Following examples how present gasification technology had been able to find a “niche” market in the refinery industry to help fund and advance their technology, ZECA has been urged to examine similar opportunities and develop a market entry strategy. The Canadian oil sands industry may present just such a scenario for the ZEC technology. Hydrogen, now reformed from natural gas, is a necessary and costly element of the oil sands upgrading process. Further, the upgrading process produces large quantities of petroleum coke with little value as a marketable commodity. This pet coke can be used as a suitable feedstock for a ZEC plant, which would then produce hydrogen for the upgrading process. ZECA will be pursuing design and economic assessments to examine how the ZEC process can be integrated with oil sands production and refining. Lastly, in relative close proximity to the oil sand region there are oil and gas fields where the produced CO₂ could be used to perform enhanced recovery duties or be sequestered.

A third area of ZECA research is to examine if the ZEC technology might have useful applications in processes to produce synthetic liquid fuels, or co-produce liquids and other products such as electric power, while maintaining zero emission to the atmosphere.

Following the events of last September, energy security is to set to become a long-term, important force in U.S. development of coal and other carbon-based energy systems, paralleling environmental security considerations, such clean air and water, and safe disposal of solid and other wastes. The ZEC concept recognizes and reinforces the combined pursuit of energy and environmental security as crucial to all future carbon-based technologies.

CONCLUSIONS

- While technical and economic uncertainties remain in a number of areas and significant work is still needed to fully test the feasibility of the ZEC power generation concept, no fatal flaws are evident from the assessments to date and the initial results show good potential for high busbar efficiency and competitive costs.
- Comparison of the ZEC concept with other power generation systems featuring CO₂ removal indicates that, when combined with sequestration, the ZEC concept has the potential to be less costly than those other technologies and competitive with natural gas combined cycle plants, even at relatively conservative fuel prices.
- The following enabling technologies were identified as requiring further R&D and engineering evaluation: hydrogasification, hot gas cleanup and contaminants removal, reforming catalysts, carbonation/calcining handling, processing and heat transfer, and SOFC technology.

- Building on the R&D results, ZECA Corp. plans to design, construct and start operating a 5-MW pilot plant within five years.
- An extensive U.S. Department of Energy-funded program for the development of a mineral carbonation process for the sequestration of CO₂ is underway. Costs have come down considerably and are on target.

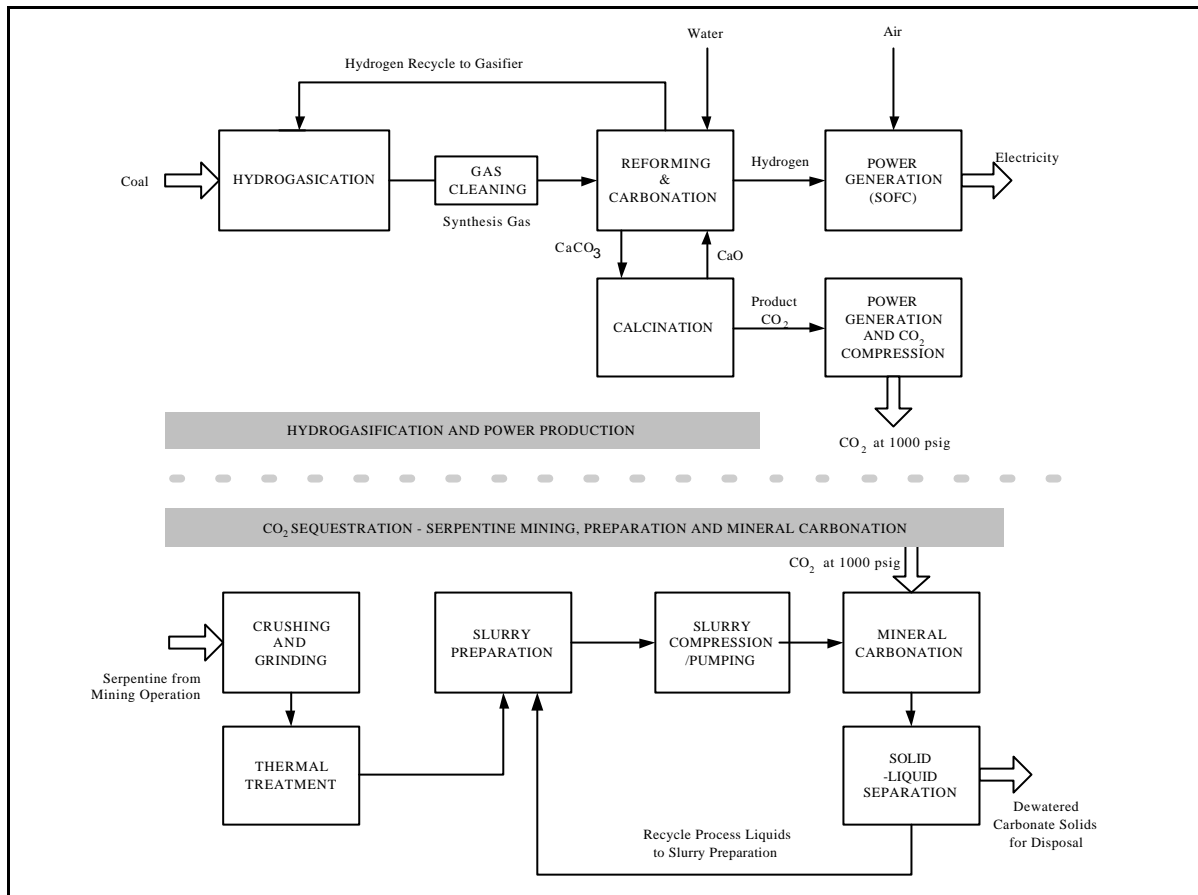


Figure 1. ZEC Technology Concept

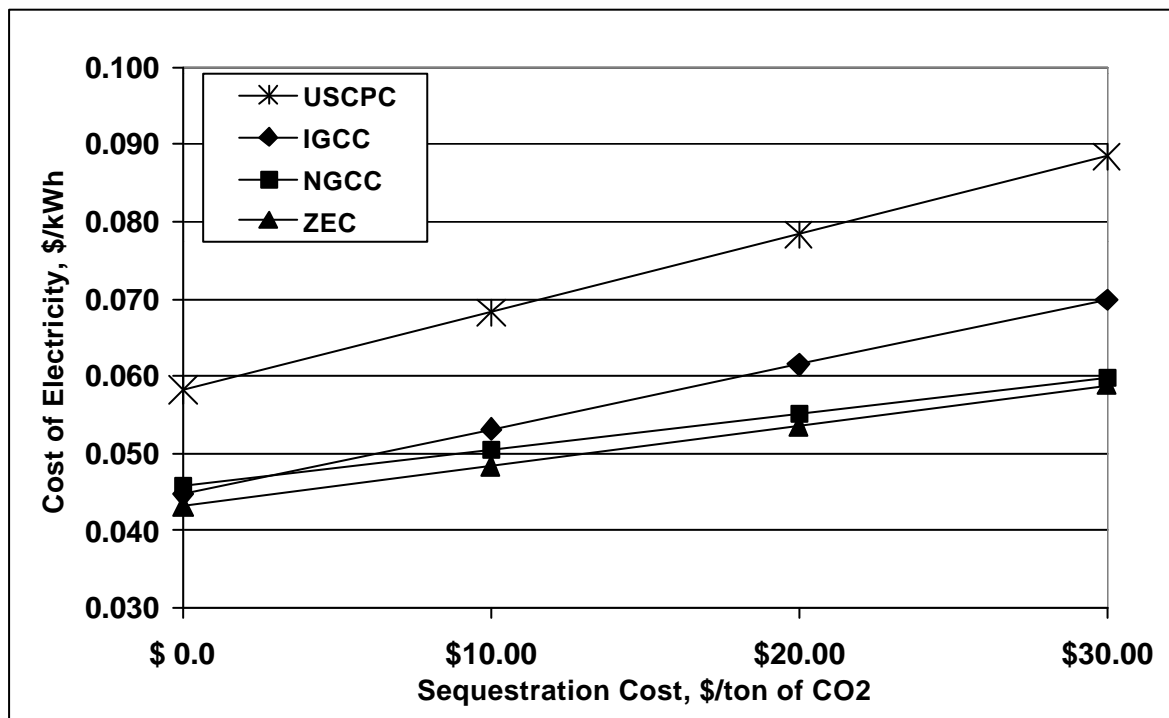


Figure 3. Comparison of Cost of Electricity for Advanced Technologies with Sequestration

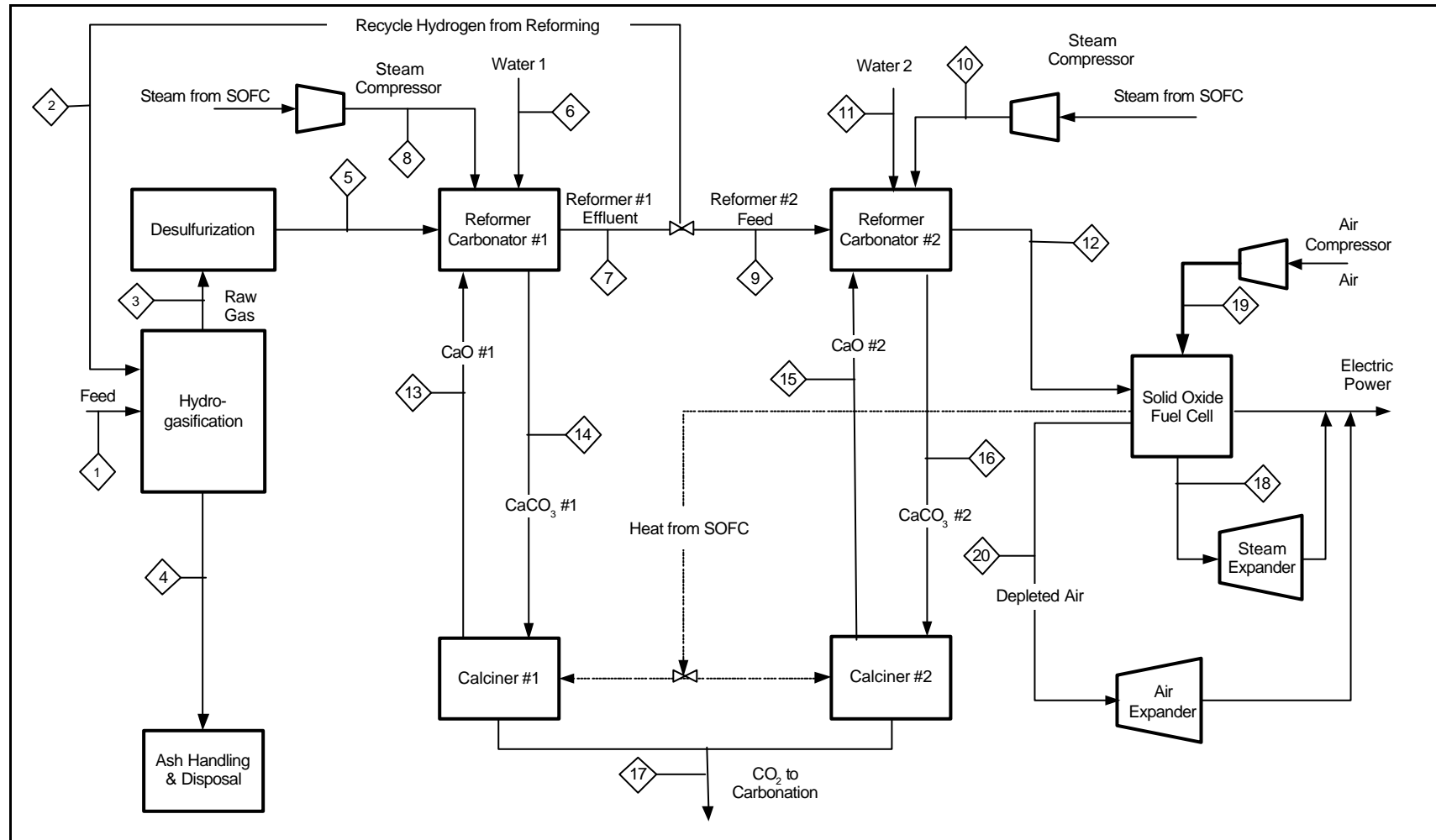


Figure 2. ZEC Hydrogasification and Power Generation Process Diagram

Table 1. Zero Emission Coal Alliance (ZECA) Members

| | | |
|-----------------------------------------------|---------------------------------------------------------------|-------------------------------------------------------|
| Energy Research Institute Calgary, Alberta | Kennecott Energy Gillette, Wyoming | RAG Coal International AG Essen, Germany |
| Arch Coal St. Louis, Missouri | Los Alamos National Laboratory Los Alamos, New Mexico | Salt River Project Phoenix, Arizona |
| Barrick Gold Elko, Nevada | Natural Resources Canada Ottawa, Ontario | SaskPower Regina, Saskatchewan |
| Caterpillar Peoria, Illinois | Ontario Power Generation Toronto, Ontario | Southern Company Wilsonville, Alabama |
| EPCOR Utilities Inc. Edmonton, Alberta | Pinnacle West (Arizona Public Service) Phoenix, Arizona | The Coal Association of Canada Calgary, Alberta |
| Fording Coal Limited Calgary, Alberta | PG&E National Energy Group Bethesda, Maryland | TransAlta Corporation Calgary, Albert |

Table 2
ZEC Gasification and Power Production Performance
(200 MW_e Net Power Module)

| Items | Units | Performance | | |
|-----------------------|----------|-----------------|------------------|---------------------------|
| | | Powder River | Pittsburgh #8 | AOSP ¹ Coke |
| Coal input | lb/h | 112,600 | 77,243 | 78,362 |
| Heating value of coal | Btu/lb | 8,800 | 12,351 | 12,850 |
| Total heat input | MM Btu/h | 991 | 954 | 1,007 |
| Heat rate | Btu/kWh | 4,950 | 4,780 | 5,040 |
| Efficiency | % HHV | 69 | 71 | 68 |

¹ Alberta oil sands petroleum coke.

Table 3
Cost Estimates
600 MW_e ZEC Gasification and Power Generation Plant

| Cost Item | Cost (\$1,000) | \$/kW |
|-------------------------------------------------|-----------------------|--------------|
| Gasification, Vessels | 145,200 | 242 |
| Gasification, Rotating Equipment | 66,000 | 110 |
| Power Generation Equipment | 535,900 | 893 |
| Product CO ₂ Heat Recovery Equipment | 42,100 | 70 |
| Coal Feed Lockhopper Equipment | 10,600 | 18 |
| Ash Discharge Lockhopper Equipment | 700 | 1 |
| Cooling Tower Equipment | 16,700 | 28 |
| Balance of Plant | 93,900 | 156 |
| Total Plant Cost¹ | 911,100 | 1,518 |

¹ Does not include process and project contingencies (see text)

Table 4. EPRI Comparison Data

| EPRI Data | NGCC1 | NGCC2 | IGCC | SCPC | USCPC |
|-------------------------------------------------------------------------------------------------------------------------------------------------|--------------|--------------|-------------|-------------|--------------|
| Efficiency, HHV % | 39.2 | 43.3 | 37.0 | 28.9 | 31.0 |
| Total Plant Cost, \$/kW | 1,010 | 943 | 1,642 | 1,981 | 1,943 |
| Total Capital Cost, \$/kW | 1,099 | 1,026 | 1,844 | 2,219 | 2,175 |
| Production Cost, cents/kWh | 3.13 | 2.92 | 2.10 | 3.18 | 2.97 |
| Cost of Electricity, cents/kWh | 5.79 | 5.41 | 6.57 | 8.56 | 8.24 |
| Incremental Cost of Electricity, cents/kWh; calculated as difference in Cost of Electricity between plants with/without CO ₂ removal | 2.37 | 2.06 | 1.33 | 3.41 | 3.14 |
| CO ₂ Removal Cost, \$/ton; calculated as the difference between plants with/without removal | 51.63 | 49.43 | 15.87 | 28.90 | 31.00 |

NGCC1: F class natural gas turbine combined cycle with CO₂ removal.

NGCC2: H class natural gas turbine combined cycle with CO₂ removal.

IGCC: Integrated gasification combined cycle, H class turbine with CO₂ removal.

SCPC: Conventional supercritical pulverized coal with CO₂ removal.

USCPC: Ultra supercritical pulverized coal with CO₂ removal.

Table 5. MIT Comparison Data

| MIT Data | IGCC 2000 ¹ | IGCC 2012 ¹ | PC 2000 ² | PC 2012 ² | NGCC 2000 ³ | NGCC 2012 ³ |
|---------------------------------------------------|---------------------------|---------------------------|-------------------------|-------------------------|---------------------------|---------------------------|
| Efficiency, LHV % | 36.1 | 43.5 | 30.9 | 36.1 | 47.8 | 54.1 |
| Efficiency, HHV % (estimated) | 32.5 | 39.2 | 27.9 | 32.5 | 43.2 | 48.8 |
| Capital Cost, \$/kW | 1,909 | 1,459 | 2,090 | 1,718 | 1,013 | 894 |
| Cost of Electricity; Capital, cents/kWh | 4.36 | 3.33 | 4.77 | 3.92 | 2.31 | 2.04 |
| Cost of Electricity; Fuel, cents/kWh | 1.17 | 0.97 | 1.37 | 1.17 | 2.09 | 1.85 |
| Cost of Electricity; O&M, cents/kWh | 1.16 | 0.84 | 1.57 | 1.16 | 0.51 | 0.44 |
| Total Cost of Electricity; cents/kWh | 6.69 | 5.14 | 7.71 | 6.26 | 4.91 | 4.33 |
| CO ₂ Removal Cost, \$/ton (calculated) | 23.27 | 16.00 | 44.13 | 29.05 | 44.90 | 37.27 |
| Incremental Cost of Electricity, cents/kWh | 1.70 | 1.04 | 3.32 | 2.16 | 1.61 | 1.23 |

¹ IGCC 2000 and 2012 represent integrated gasification combined cycle plants with CO₂ removal, adjusted for estimated improvements in the time from 2000 to 2012.

² PC 2000 and PC 2012 are similar pulverized coal-fired plants with CO₂ removal.

³ NGCC 2000 and NGCC 2012 are similar natural gas-fired turbine combined cycle plants with CO₂ removal.

Table 6
Comparison of Advanced Power Technologies with CO₂ Removal

| | ZEC 600 MW _e | EPRI ¹ | | | | |
|-----------------------------------------------------------------|----------------------------|-------------------|------------|------------|--------------|--------------|
| | | NGCC1 | NGCC2 | IGCC | SCPC | USCPC |
| Efficiency, HHV % | 68.9 | 39.2 | 43.3 | 37.0 | 28.9 | 31.0 |
| Tons of CO ₂ per year per MW _e removed | 4,090 | 3,630 | 3,280 | 6,620 | 8,510 | 7,920 |
| Total Plant Cost, \$/kW | 1,520 | 860 | 790 | 1,400 | 1,710 | 1,680 |
| Cost of Electricity, cents/kWh | 4.32 | 4.59 | 4.25 | 4.47 | 6.08 | 5.82 |
| | MIT ² | | | | | |
| | IGCC 2000 | IGCC 2012 | PC 2000 | PC 2012 | NGCC 2000 | NGCC 2012 |
| Efficiency, HHV % | 32.5 | 39.2 | 27.9 | 32.5 | 43.2 | 48.8 |
| Tons of CO ₂ per year per MW _e removed | 5,760 | 5,120 | 5,930 | 5,860 | 2,830 | 2,600 |
| Capital Cost, \$/kW | 1,909 | 1,459 | 2,090 | 1,718 | 1,013 | 894 |
| Cost of Electricity; \$/kWh | 5.57 | 4.29 | 6.49 | 5.25 | 4.32 | 3.81 |

¹ Total Plant Costs less costs for process and project contingencies.

² Capital Costs with contingencies and owners' costs likely included.

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For additional information please visit the ZECA, Los Alamos National Laboratory, Columbia University and Nexant web sites:

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